# Feasibility neutronic design for the reactor core configurations of a 5 MWth transportable block-type HTR

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**Abstract** Small long-life transportable high temperature gas-cooled reactors (HTRs) are interesting because they can safely provide electricity or heat in remote areas or to industrial users in developed or developing countries. This paper presents the neutronic design of the U-Battery, which is a 5 MWth block-type HTR with a fuel lifetime of 5–10 years. Assuming a reactor pressure vessel diameter of less than 3.7 m, some possible reactor core configurations of the 5 MWth U-Battery have been investigated using the TRITON module in SCALE 6. The neutronic analysis shows that Layout 12×2B, a scattering core containing 2 layers of 12 fuel blocks each with 20% enriched $^{235}$U, reaches a fuel lifetime of 10 effective full power years (EFPYs). When the diameter of the reactor pressure vessel is reduced to 1.8 m, a fuel lifetime of 4 EFPYs will be achieved for the 5 MWth U-Battery with a 25-cm thick graphite side reflector. Layouts 6×3 and 6×4 with a 25-cm thick BeO side reflector achieve a fuel lifetime of 7 and 10 EFPYs, respectively. The comparison of the different core configurations shows that, keeping the number of fuel blocks in the reactor core constant, the annular and scattering core configurations have longer fuel lifetimes and lower fuel cost than the cylindrical ones. Moreover, for the 5 MWth U-Battery, reducing the fuel inventory in the reactor core by decreasing the diameter of fuel kernels and packing fraction of TRISO particles is more effective to lower the fuel cost than decreasing the $^{235}$U enrichment.

**Key words** Feasibility design, Reactor core configurations, Transportable reactors, Small modular reactors, Block-type HTRs

## 1 Introduction

In the past fifty years, the size of nuclear reactors has grown from 60 MWe to more than 1600 MWe in order to make full use of economy of scale[1]. However, because large-size nuclear reactors usually require high capital investment and rely heavily on the infrastructure of reactor sites, this has motivated to develop small modular nuclear reactors (SMRs) based on different reactor technologies[2–4], especially for developing countries and remote areas off main grids. The SMRs can be fabricated in modularity and transported to sites by rail, barge, truck, etc. After a long operation (e.g., 5–10 years), the SMRs can be brought back to factories for refueling or directly replaced by new ones. Moreover, the 5–10 SMRs in a site may become a nuclear power plant (NPP) with a comparable power level to large NPPs.

Over the last 30 years, the inherent safety of small modular HTRs (high temperature gas-cooled reactors) has been validated directly by experiments [5–7]. Our previous paper[8] presents the neutronic designs of a 20 MWth long-life block-type HTR, called as U-Battery, which can be commercialized in the near future. For the 20 MWth U-Battery, the reference reactor core configuration adopts 148(=37×4) fuel blocks developed for the GT-MHR project[9], a 29-cm-thick graphite side reflector, and 50-cm-thick top and bottom graphite reflectors. Although the outer diameter of the reactor pressure vessel (RPV) of the U-Battery is limited to 3.7 m based on the maximum size of road transport, the weight of the whole reactor core of the 20 MWth U-Battery is a quite large,

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decreasing the flexibility for road transport of the U-Battery. In order to strengthen the transportability of the U-Battery, two designs for a 5 MWth U-Battery are proposed in this paper. The first design described in Section 2 uses a RPV with 3.7-m diameter in order to make full use of neutron economy, while the second described in Section 3 uses a RPV with 1.8-m diameter to minimize the reactor core of the U-Battery.

## 2 A 5 MWth U-Battery with 3.7 m RPV in diameter

This section describes a U-Battery reactor core with thermal power of 5 MWth. Because the thermal-hydraulic design of the 20 MWth U-Battery leads to the volume-averaged temperatures of the 727°C reactor core, and 227°C top, 727°C bottom and 527°C side reflectors[10,11], the nuclear design of the 5 MWth reactor core adopted these temperatures as the reference temperature of the mixtures. All calculations are implemented by TRITON module in SCALE 6[12].

At the 3.7-m outer diameter of the RPV, Fig.1 shows the eight reactor core configurations of the 5 MWth U-Battery. Layout 37×1 has a very small height of the reactor core and thus RPV, which has in total 37 fuel blocks in the reactor core. Layouts 19×2 and 18×2 have 38 and 36 fuel blocks, respectively. Layout 6×2 is modeled in order to compare with the smaller reactor core designs with very thin side reflectors in the next section. Analyzed in the previous paper[8], the scatter and annular core configurations of 20 MWth U-Battery have better neutronic performance because of a larger mass ratio of graphite to uranium and thus better neutron moderation. Two scatter and one annular core configurations with 24(12×2) fuel blocks are shown in Fig.1 (IV), (V) and (VI), respectively.

The neutronic calculations for the eight reactor core configurations are shown in Table 1.

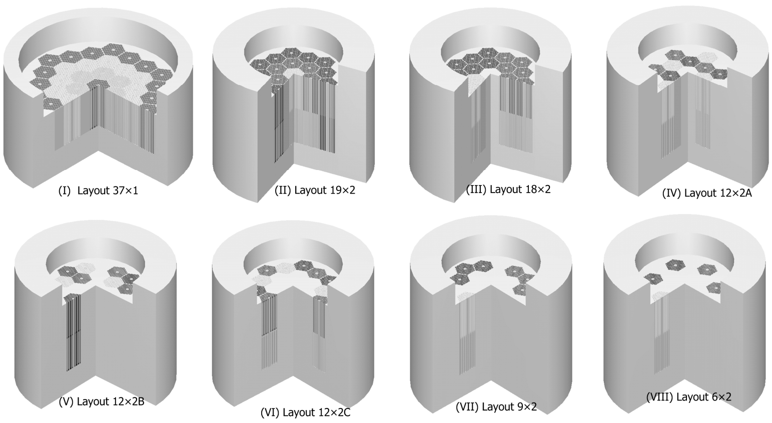


**Fig.1** Reactor core configurations of 5 MWth U-Battery with 3.7-m RPV in diameter (The top reflectors have been removed in the reactors for illustrating the reactor core).

**Table 1** $k_{\mathrm{eff}}$ and fuel cost of the eight configurations for the 5 MWth U-Battery

| Cases | Configuration(1) | $k_{\mathrm{eff,BOL}}$ | $k_{\mathrm{eff,EOL}}$(2) | Uranium mass / kg | Fuel cost(3)/ M$ |
|---|---|---|---|---|---|
| 1 | Layout 37×1 | 1.153 | 0.964 (7.0) | 320.5 | 5.86 |
| 2 | Layout 19×2 | 1.216 | 1.028 | 329.2 | 6.02 |
| 3 | Layout 18×2 | 1.238 | 1.045 | 311.8 | 5.70 |
| 4 | Layout 12×2A | 1.243 | 0.989 (8.5) | 207.9 | 3.80 |
| 5 | Layout 12×2B | 1.270 | 1.019 | 207.9 | 3.80 |
| 6 | Layout 12×2C | 1.249 | 1.004 | 207.9 | 3.80 |
| 7 | Layout 9×2 | 1.224 | 0.889(6.7) | 155.9 | 2.85 |
| 8 | Layout 6×2 | 1.193 | 0.582(4.0) | 130.9 | 1.89 |

Note: (1) Fuel kernel radius: 0.25 mm; Fuel compact radius: 0.6225 cm; Packing fraction of TRISO particles: 0.3. (2) The $k_{\mathrm{eff}}$ at 10 EFPYs (the possible maximum fuel lifetime when $k_{\mathrm{eff}} < 1$). (3) The 20% enriched $^{235}$U: 18.281 k$/kgHM, where manufacture cost is 1200 $/kgU, and final disposition cost is 1500 $/kgHM.

The second column shows the names of reactor core configurations. The third and fourth columns are the effective multiplication factors at beginning of life (BOL) and end of life (EOL), respectively. If the effective multiplication factor of a certain configuration is less than unity, the data in the bracket is the possible maximum fuel lifetime for the specific configuration; otherwise this data is given after operation time of 10 years. The fifth column shows the uranium total mass in the reactor core, and the sixth column shows the fuel cost. All eight reactor core configurations use 20% enriched $^{235}$U.

Case 2 consists of 38 fuel blocks and reaches a fuel lifetime of 10 effective full power years (EFPYs), with resulting $k_{\mathrm{eff}}$ at EOL of 1.028. Case 3 consists of 36 fuel blocks, and the $k_{\mathrm{eff}}$ is 1.045 at EOL. Although the number of fuel blocks of Layout 18×2 is less than that of Layout 19×2, the $k_{\mathrm{eff}}$ of the former is larger than the latter because of better neutron moderation. Although the reactor core of Layout 37×1 consists of 37 fuel blocks, which is larger than the number of fuel blocks of Layout 18×2, it is not able to reach a 10-EFPY fuel lifetime, and the maximum possible fuel lifetime is 7.0 EFPYs, because of the 29-cm-thin side reflector and a large neutron leakage. If the number of fuel blocks reduces to 24(12×2), Cases 5 and 6 just reach a 10-EFPY fuel lifetime, while Case 4 fails. This means that the reactor core configuration is of importance, even though the number of fuel blocks is identical. Lumping fuel blocks increase the resonance escape probability. For Layout 12×2B, the 24 fuel columns are divided into three groups. Each group consists of 4 fuel columns (each containing two fuel blocks), which is surrounded by graphite. For this configuration, neutrons escaping from a particular group of fuel blocks are easily moderated in the surrounding graphite blocks, before they have an interaction with the uranium in another group of fuel blocks. Layouts 9×2 and 6×2 are not able to achieve a 10-EFPY fuel lifetime because the number of fuel blocks is too small. The needed uranium mass of Layout 12× 2B decreases by 36.8%, compared with the uranium mass of Layout 19×2.

Since the effective multiplication factors of both Layouts 19×2 and 18×2 are larger than unity at 10 EFPYs, there are three ways to improve the economic performance of the two configurations. The first is to extend the fuel lifetime of the U-Battery until the $k_{\mathrm{eff}}$ of the reactor is unity. The second is to lower further the fuel costs by decreasing the $^{235}$U enrichment, while keeping the fuel kernel size ($R_{\mathrm{k}}$) and the packing fraction (PF) of the TRISO particles constant. Cases 1 and 4 in Table 2 are the results of this way. It shows that the enrichment of $^{235}$U reduces by 2% for Layouts 19×2; and for 18×2, 3.2%, thus their fuel cost reduces by 9% and 15.4%, respectively.

**Table 2** Fuel cost of different fuel compositions for the 5 MWth U-Battery

| Case | Configuration(1) | Enrich / % | PF | $R_{\mathrm{k}}$ / mm | Uranium Mass / kg | Fuel cost(2)/ M$ |
|---|---|---|---|---|---|---|
| 1 | Layout 19×2 | 18.0 | 0.30 | 0.25 | 329.2 | 5.48 |
| 2 | Layout 19×2 | 20.0 | 0.217 | 0.25 | 238.1 | 4.353 |
| 3 | Layout 19×2 | 20.0 | 0.30 | 0.20 | 238.0 | 4.351 |
| 4 | Layout 18×2 | 16.8 | 0.30 | 0.25 | 311.9 | 4.82 |
| 5 | Layout 18×2 | 20.0 | 0.20 | 0.25 | 207.9 | 3.80 |
| 6 | Layout 18×2 | 20.0 | 0.30 | 0.19 | 208.2 | 3.81 |
| 7 | Layout 12×2B | 20.0 | 0.278 | 0.25 | 192.6 | 3.52 |
| 8 | Layout 12×2B | 20.0 | 0.30 | 0.23 | 186.1 | 3.40 |

Note: (1) Fuel compact radius: 0.6225 cm. (2) Fuel costs of 20%, 18% and 16.8% enriched $^{235}$U are 18.281 k$/kgHM, 16.647 k$/kgHM and 15.668 k$/kgHM, respectively.

The third way of increasing the economic performance of Layouts 19×2 and 18×2 is to decrease the inventory of uranium in the reactor core by changing the geometric parameters of the TRISO particles, i.e., fuel kernel radius and PF, while keeping the enrichment of the $^{235}$U constant. Cases 2 and 3 as well as Cases 5 and 6 in Table 2 are its results for Layouts 19×2 and 18×2, respectively. Comparison of Case 2 with Case 3 shows that reducing the fuel kernel radius $R_{\mathrm{k}}$ and PF of TRISO particles is equivalent from neutronic point of view, because the fuel costs of both cases are almost identical. From the viewpoint of mechanical stress of fuel kernels, keeping the kernel radius of 0.25 mm is positive, so it is recommended to keep the fuel kernel radius constant and reduce the PF of TRISO particles. If so, the fuel costs of Layouts

19×2 and 18×2 decrease further by 20.6% and 21.1%, respectively. For Layout 12×2B, reducing the fuel kernel radius is better than reducing the PF of TRISO particles, but their difference is rather small.

## 3 A 5 MWth U-Battery with 1.8 m RPV in diameter

In order to further decrease the reactor weight for better transportability of the U-Battery, reducing the diameter of RPV is effective because this can effectively reduce the reactor core weight of RPV. The inner diameter of RPV is fixed to 1.8 m, because it is the same as the inner diameter of flasks for the transportation of PWR or BWR spent fuel assembles, and the transportation experience of the flasks over the world can be utilized for the transportation of the U-Battery. For the RPV with the 1.8-m inner diameter, the 6 fuel columns are the possible maximum number in the reactor core, and the number of fuel blocks in the axial direction and the material of the side reflector are two key design parameters as shown in Fig.2. If the height of the reactor core is limited to about 4 m, the 4 fuel blocks in the axial direction of the reactor core are the maximum value.

In terms of 1.8-m RPV indiameter, the results of the nuclear design are shown in Tables 3 and 4 for the U-Battery with graphite and BeO side reflectors, respectively. The second column shows the reactor core configuration of the U-Battery. The third and fourth columns are the parameters of the side reflector, i.e., material and maximum thickness. The fifth column shows the maximum fuel lifetime for each reactor core configuration, and the sixth column shows the total reactor mass, including the fuel blocks, central, top, bottom and side reflectors, barrel (assumed 5 cm) and RPV (assumed 10 cm). Because the reactor core is very small and the side reflector is very thin, the barrel and RPV were modeled for all Cases in this section to include their reflection effect.

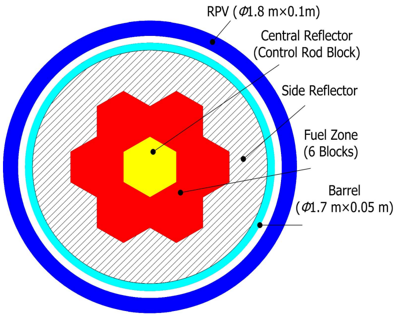


**Fig.2** Reactor core configuration of the U-Battery with 1.8-m RPV in diameter.

### 3.1 Graphite side reflector

Group A in Table 3 contains three basic Cases for the 5 MWth U-Battery in terms of 1.8-m RPV in diameter. The number of fuel blocks for Cases A.1is 12; and for A.2, 18; and for A.3, 24. The material of the side reflector is nuclear graphite, whose possible maximum thickness is 25 cm if the thickness of the barrel is 5 cm and gas gap between barrel and RPV is 5 cm. As shown in Table 3, the maximum possible fuel lifetime of Layouts 6×2, 6×3 and 6×4 are 0.4, 2.0 and 3.0 EFPYs, respectively. Case A.1 in Table 2 has the same number of fuel blocks as Case 8 in Table 1, but the difference in the effective multiplication factors is very large. Assuming Case 8 in Table 1 has a sufficiently thick side reflector, Case A.1 in Table 2 has very poor neutronic performance because a large fraction of neutrons leaks from the reactor core though the RPV.

**Table 3** Fuel lifetime and total mass of the reactor configurations with graphite side reflector

| Case | Configuration | Material | Thickness / cm | Lifetime | Total Mass[1]/ tons |
|---|---|---|---|---|---|
| | | A. Basic design (5.0 MWth) | | | |
| A.1 | Layout 6×2 | Graphite | 25 | 0.4 EFPYs | 28.4 |
| A.2 | Layout 6×3 | Graphite | 25 | ~2.0 EFPYs | 36.8 |
| A.3 | Layout 6×4 | Graphite | 25 | 3.0 EFPYs | 45.2 |
| | | B. External side reflector (Thickness = 50 cm) | | | |
| B.1 | Layout 6×2 | Graphite | 25 | 0.4 EFPYs | 28.4 |
| B.2 | Layout 6×3 | Graphite | 25 | 2.0 EFPYs | 36.8 |
| B.3 | Layout 6×4 | Graphite | 25 | 3.0 EFPYs | 45.2 |
| | | C. 1 MWth design | | | |
| C.1 | Layout 6×3 | Graphite | 25 | 10 EFPYs | 36.8 |
| C.2 | Layout 6×4 | Graphite | 25 | 18 EFPYs | 45.2 |

Note: Total mass includes the mass of fuel blocks, reflectors, barrel and RPV without upper and lower heads.

Since the small reactor core faces large neutron leakage, external side reflector (ESR) located outside the RPV is considered to be used to reflect neutrons, which leak from the reactor core. Group B in Table 3 shows the neutronic effects of the ESR. Comparing pairwise group B with group A, the neutronic effects of the 50-cm-thick ESR can be neglected. This means that the RPV and barrel reflect the neutrons back to the reactor core. So it is recommended to model the barrel and RPV for the neutronic analysis of the U-Battery with a thin side reflector.

Group C is the results of two configurations for a 1 MWth U-Battery. If the thermal power of the U-Battery decreases to 1 MWth, the maximum fuel lifetimes of Layouts 6×3 and 6×4 are 10 and 18 EFPYs, respectively. Comparing Cases C.1 and C.2 with A.2 and A.3, an approximately linear relationship between thermal power and fuel lifetime is clear. If so, the maximum thermal power of the U-Battery is about 4 MWth if the fuel lifetime is fixed to 5 EFPYs.

In terms of the results of groups A, B and C, it is impossible to achieve a design of the 5 MWth U-Battery with a fuel lifetime of 5 EFPYs and 1.8-m RPV in diameter when the side reflector is 25-cm-thick graphite. Case 8 in Table 1 shows that a reactor core with 12 fuel blocks is able to achieve 4 EFPYs if there is a sufficiently thick side reflector, even though the model does not include the neutron reflection effect of the barrel and RPV. In other words, all reactor configurations in Table 3 have very poor neutron economy because of very thin side reflectors. Since the ESR is not effective to reflect the leaked neutrons out of the RPV because of the double blockage of the barrel and RPV, the only way to increase the neutron economy of the U-Battery with 1.8 meter RPV in diameter is to improve the neutronic performance of the side reflector.

### 3.2 Beryllium oxide side reflector

Beryllium is a good moderator material from neutronic point of view, which has a larger moderating power and higher density than graphite. Compared with metallic beryllium, beryllium oxide (BeO) with higher melting temperature and density is used for the U-Battery with 1.8-m RPV in diameter. Three groups of reactor core configurations are investigated (Table 4).

**Table 4** Fuel lifetime and total mass of the reactor configurations with BeO side reflector

| Case | Configuration | Material | Thickness / cm | Lifetime | Total Mass[1]/tons |
|---|---|---|---|---|---|
| | | D. Limit design ($\rho$ = 3.0 g/cm$^3$) | | | |
| D.1 | Layout 6×3 | BeO | 25 | ~ 8 EFPYs | 45.9 |
| D.2 | Layout 6×4 | BeO | 25 | 10.5 EFPYs | 56.4 |
| | | E. More realistic design ($\rho$ = 2.8 g/cm$^3$) | | | |
| E.1 | Layout 6×3 | BeO | 15 | 6.0 EFPYs | 41.7 |
| E.2 | Layout 6×3 | BeO | 20 | ~7.0 EFPYs | 43.2 |
| E.3 | Layout 6×3 | BeO | 25 | 7.0 EFPYs | 44.5 |
| E.4 | Layout 6×4 | BeO | 25 | 10 EFPYs | 54.7 |
| | | F. 10 MWth design ($\rho$ = 2.8 g/cm$^3$) | | | |
| F.1 | Layout 6×3 | BeO | 25 | 3.5 EFPYs | 44.5 |
| F.2 | Layout 6×4 | BeO | 25 | 5.0 EFPYs | 54.7 |

Note: Total mass includes the mass of fuel blocks, reflectors, barrel and RPV without upper and lower heads.

The first group (group D) is the limit design of the reactor core, because all the space between the reactor core and barrel is filled with BeO, and a high density of BeO, 3.0 g/cm$^3$, is used. Cases D.1 and D.2 achieve 8 and 10.5 EFPY fuel lifetime, respectively. The second group, i.e., group E, shows the influence of the thickness of BeO side reflector. Comparing Cases E.2 and E.3 shows that the 20-cm-thick BeO side reflector is enough for the side reflector of the U-Battery from neutronic point of view, even though the BeO density decreases from 3.0 g/cm$^3$ to 2.8 g/cm$^3$. From thermal-hydraulic point of view, it is really helpful to have a 5-m annular space between the side reflector and barrel. This means that there is a small space to accommodate the side thermal insulation in order to protect the barrel and RPV. Group F shows the results of two reactor core configurations of the U-Battery with 10 MW thermal powers for the same-size RPV. Comparing Cases F.1 and F.2 with

Cases E.3 and E.4, respectively, the fuel lifetime of the reactor core is still linear to the thermal power for the two Cases of group F. From economic point of view, the 10 MWth U-Battery with a 5-EFPY fuel lifetime is more economic than the 5 MWth U-Battery with a 10-EFPY fuel lifetime.

## 4 Conclusion

The reactor core configurations of a transportable 5 MWth HTR with 5–10 effective full power years (EFPYs), called U-Battery, have been investigated by the TRITON module in Scale 6. In order to emphasize its transportability of the 5 MWth U-Battery, the diameter of RPV is limited to 3.7 m and 1.8 m.

For the 3.7-m RPV in diameter, the reactor core with 24 fuel blocks loaded 20% enriched $^{235}U$ reaches a fuel lifetime of 10 EFPYs for the 5 MWth U-Battery. Comparisons of the different reactor core configurations with 24 fuel blocks show that Layout 12×2B, a scattering core, achieves the lowest fuel cost. Moreover, reducing the fuel inventory of the reactor core by decreasing the diameter of the fuel kernels and the packing fraction of the TRISO particles decreases the fuel cost of Layout 12×2B by 11%.

When decreasing the RPV diameter from 3.7 m to 1.8 m, it is possible to achieve a fuel lifetime of 4 EFPYs for the 5 MWth U-Battery with a graphite side reflector. If nuclear graphite is replaced by BeO, Layouts 6×3 and 6×4 with the 25-cm-thick BeO side reflector achieve 7 EFPYs and 10 EFPYs, respectively, for the 5 MWth U-Battery. The 20-cm-thick BeO side reflector is sufficiently thick from neutronic point of view. Moreover, it provides more space for the side thermal insulation to protect the barrel and RPV. Future work will focus on the design of the reactivity control system of Layouts 6×3 and 6×4 with 20-cm-thick BeO side reflector, and on the coupled neutronic /thermal-hydraulic evaluation of the different designs.

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